

Medium-modified fragmentation functions

R. Sassot¹ M. Stratmann² and P. Zurita¹ *

1- Departamento de Fisica, FCEN, Universidad de Buenos Aires
Pabellon 1, Ciudad Universitaria (1428) Buenos Aires, Argentina

2- Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany
Institut für Theoretische Physik und Astrophysik, Universität Würzburg, 97074 Würzburg, Germany

We discuss preliminary results on medium-modified fragmentation functions obtained in a combined NLO fit to data on semi-inclusive deep inelastic scattering off nuclei and hadroproduction in deuteron-gold collisions.

1 Motivation

In the last few years there has been a significant improvement in the perturbative QCD description of hadroproduction processes, and more specifically, in the precise determination of fragmentation functions [1]. One of the most interesting features of these extractions is that they not only reproduce the usual data on electron-positron annihilation into hadrons, but they describe as well other processes like semi-inclusive deep inelastic scattering (SIDIS) and hadroproduction in proton-proton collisions, with remarkable precision. This demonstrates the ideas of factorization and universality, which are the starting points for the perturbative QCD description, in the kinematical domain accessed by these experiments.

In spite of this apparently successful scheme, fragmentation functions (FFs) are far from giving us the whole picture of hadronization; they are an efficient way to encode the non-perturbative information required for computing cross sections, but they don't tell us much about, for instance, the space-time evolution of the hadron formation, the origin of the differences between the different species, and many other non perturbative key issues.

To have an insight into these features, we need to attack the problem from a different angle, that could be for example, studying how hadronization proceeds in a nuclear environment. In recent years there has been an increasing number of experiments pointing in this direction, exploring hadroproduction off nuclear targets with mass A , such as very precise semi-inclusive eA measurements by HERMES [2], as well as experiments using dAu collisions at the RHIC [3, 4]. Both processes show clear signals of non trivial nuclear dependence in the hadronization mechanism, that needs to be understood. Additionally, this information serves as baseline for heavy ion research programs ongoing at RHIC and projected for LHC, aiming at unravelling the properties of hot and dense QCD matter [5].

In parallel with the availability of data, several theoretical calculations and models designed to describe the nuclear dependence have been proposed, some of them putting the emphasis on the interactions of hadrons and “pre-hadrons” in the nuclear medium, others focussing on the interactions of the “seed partons” with the medium. More recently, it has also been suggested that FFs could obey different energy scale dependence because of the nuclear medium. Most models reproduce with different success features of the data, in spite of very different, even orthogonal, approaches and ingredients [5].

In our approach, rather than proposing a particular mechanism, in a first step we try to isolate the medium induced modification of the FFs as precisely as possible, factoring out

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the standard knowledge on nuclear effects in the parton densities, as seen in deep inelastic scattering or Drell Yan processes with nuclei [6], and the QCD dynamics inherent to hard processes at NLO accuracy. In other words, we fit medium-modified fragmentation functions (nFFs), assuming (or testing) factorization and universality in a nuclear environment.

2 Convolutional Approach:

Rather than fitting from scratch the nFFs, which would take as many parameters as the standard or vacuum FFs, plus some more to represent the nuclear size or density dependence, in the following we choose to relate the nFFs to the standard ones by a convolution:

$$D_{i/A}^h(z, Q_0^2) = \int_z^1 \frac{dy}{y} W_i(y, A, Q_0^2) D_i^h\left(\frac{z}{y}, Q_0^2\right), \quad (1)$$

where the weight function $W_i(y, A, Q_0^2)$ parameterizes nuclear effects in FFs at a given initial scale Q_0 . The scale dependence of nFFs is then determined by ordinary NLO evolution equations. A simple delta function $\delta(1-y)$ as weight would imply no nuclear effects, while a shift in its argument, i.e. $\delta(1-\epsilon-y)$, would represent a shift in the momentum fraction as suggested, for example, by some energy loss mechanism. A more general weight function like

$$W_i(y, A, Q_0^2) = n_i y^{\alpha_i} (1-y)^{\beta_i}, \quad (2)$$

can parameterize effects not necessarily related to modifications the parton's momentum, such as hadron or pre-hadron attenuation or enhancement, with a great economy of parameters and, at the same time, retaining the information on the vacuum FFs. The A dependence of the weights can easily be included in the coefficients taking them as smooth functions of A . On the other hand, convolutional integrals are the most natural language for parton dynamics beyond the LO and allow the application of the Mellin transform technique in the NLO computation of the scale dependence and cross section estimates.

The convolutional approach has been shown to be specially effective in the extraction of initial state nuclear effects in inclusive DIS and Drell Yan processes at NLO accuracy [6]. For nFFs this is also the case, and it can be shown that an extremely simple functional form for the weights with very few parameters can reproduce the main features of the available data. However, since we are interested in obtaining an accurate parameterization, we implement more flexible weights to account for mechanisms other than global shifts in momentum but still preserving factorization. Specifically, we adopt the following ansatz:

$$W_q(y, A, Q_0^2) = n_q \delta(1 - \epsilon_q - y) + n'_q y^{\alpha_q} (1-y)^{\beta_q} \quad (3)$$

$$W_g(y, A, Q_0^2) = n_g \delta(1 - \epsilon_g - y) + n'_g y^{\alpha_g} (1-y)^{\beta_g} \quad (4)$$

discriminating between quarks and gluons. In order to enhance the sensitivity of the fit to the gluon fragmentation, it is essential to include in the fit also hadroproduction rates from dAu collisions at RHIC [3, 4]. The A dependence of the coefficients is implemented as $n_i = \lambda_{n_i} + \gamma_{n_i} A^{\delta_{n_i}}$. In most cases, however, λ can be set to zero or to unity due to the vanishing of nuclear effects as $A \rightarrow 1$. The assumption of a linear behavior ($\delta = 1$) does not spoil the quality of the fit.

Results of a fit with such an ansatz can be found in Fig. 1-3, for SIDIS pion multiplicities off different nuclei from HERMES [2] (rates are normalized to a deuterium target), neutral and charged pion production in dAu collisions from PHENIX [3] and STAR [4], respectively.

The dashed lines represent the estimates for these cross sections computed by taking into account nuclear effects *only* for the PDFs. The solid lines refer to our results with nuclear modifications also in the FFs. We obtain an overall $\chi^2 = 350.45$ for 368 data points and 17 parameters, resulting in $\chi^2/d.o.f = 0.997$. Focusing on SIDIS data in Fig. 1, the quality of the fit is quite impressive, and even the x_{Bj} (or ν) dependence is reproduced although the weights in Eqs. 3 and 4 and the nFFs only depend on z as required in a factorized approach. In addition, there seems to be no conflict with the standard (vacuum) Q^2 dependence assumed in our fit. RHIC data are also reproduced well as shown in Figs 2 and 3.

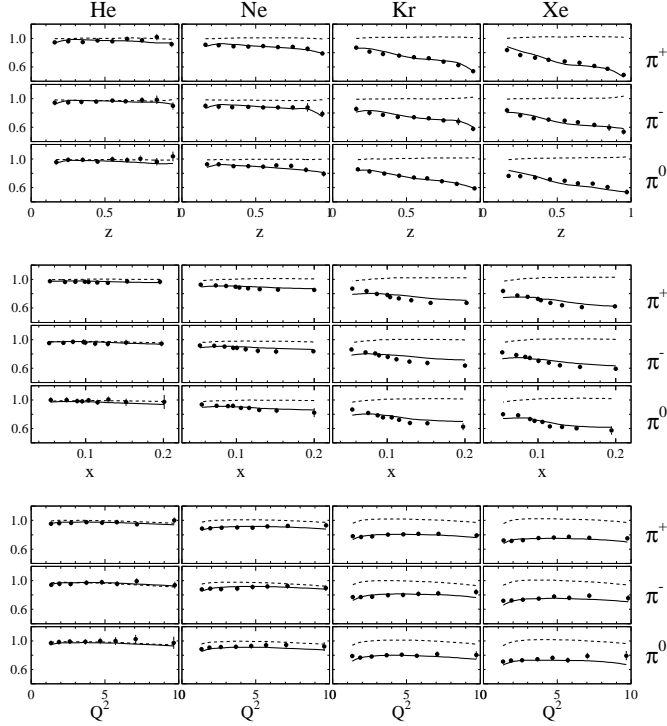


Figure 1: Pion SIDIS multiplicities from HERMES

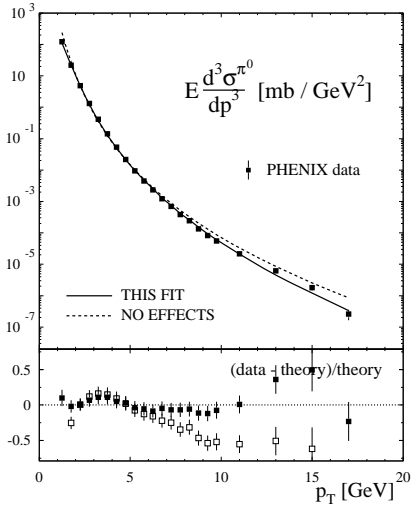


Figure 2: π^0 production in dAu collisions

The logarithmic fall off of the cross section over four orders of magnitude hinders the comparison between data and the theoretical estimates with and without nFFs. The differences are sizable, as shown in the lower panel of Fig. 2: filled and open squares are the results for “(data-theory)/theory” for fits with and without modified FFs, respectively. PHENIX data indicate a significant suppression at larger p_T , while STAR data only hint at such a behavior towards the end of the more limited p_T range. Even though the fit follows the data down to very low p_T , this needs to be taken with extreme caution since possible soft contributions may spoil factorization, and standard PDFs and FFs do not give a satisfactory description of pp data at NLO below $p_T \simeq 2$ GeV.

In Table 1 we present the values obtained for the 17 free parameters of the fit. Table 2 shows the values the coefficients in the weight functions in Eqs. 3 and 4 take for different nuclei using the parameters in Table 1. As it can be noticed, the A dependence of the coefficients is rather smooth and typically linear for A not too small. Quark and gluon coefficients are found to be rather different. In the case of quarks (and antiquarks) the main modification due to the nuclear medium is related to the first term in Eq. 3, associated to a shift ϵ_q in the momentum fraction. This shift is typically small, but introduces a non trivial z dependence, and increases linearly with A . The normalization of this term, in turn, decreases with A leading to an overall suppression. More than 80% of the nuclear modification comes from this term, while the second term represent a smaller effect. For gluons, both the first and the second term compete resulting in a much more pronounced effect.

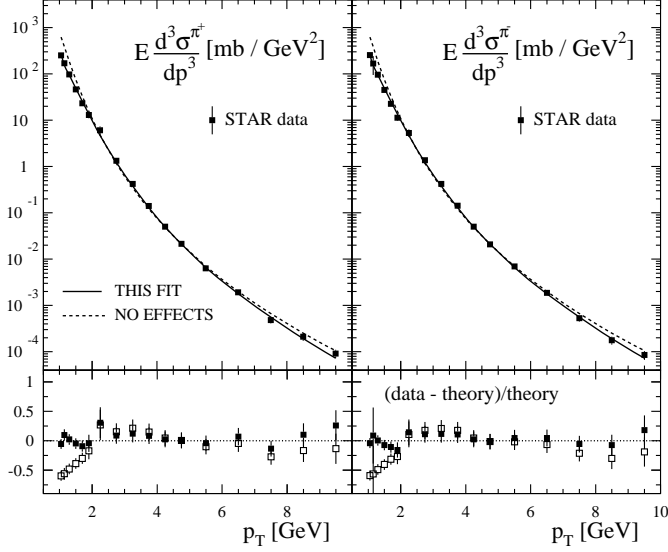


Figure 3: π^\pm production in dAu collisions

	n_q	ϵ_q	n'_q	α_q	β_q	n_g	ϵ_g	n'_g	α_g	β_g
λ	1	0	0	27.27	33.77	1	0	0	16.05	49.75
γ	-0.045	0.00015	0.0016	-0.045	-1.932	0.219	0.0007	-0.857	0.021	-0.128
δ	0.458	1	1	1	1	0.122	1	0.078	1	1

Table 1: Parameters describing the medium-modified FFs at NLO accuracy

A	n_q	ϵ_q	n'_q	α_q	β_q	n_g	ϵ_g	n'_g	α_g	β_g
He	0.913	0.001	0.006	27.095	30.711	1.260	0.003	-0.956	16.142	49.243
Ne	0.818	0.003	0.032	26.374	28.534	1.317	0.015	-1.085	16.480	47.190
Kr	0.649	0.013	0.134	23.490	25.317	1.377	0.063	-1.215	17.830	38.979
Ze	0.570	0.020	0.210	21.372	23.967	1.398	0.098	-1.258	18.822	32.949
Au	0.481	0.030	0.315	18.398	22.538	1.419	0.147	-1.299	20.214	24.481

Table 2: Coefficients of the weight functions in Eqs. 3 and 4 for different nuclei

It is also enlightening to analyze the ratios of the nuclear and vacuum fragmentation functions as a function of z for a given Q^2 , as shown in the left panels of Fig. 4. We also show the nFFs themselves in the right panels, and always at $Q^2 = 10 \text{ GeV}^2$.

For quarks and anti-quarks the main effect seems to be a reduction in the fragmentation probability increasing with z and with nuclear mass A . There is a significant drop at small z ($z < 0.1$), however, neither the nuclear nor the vacuum fragmentation functions are well constrained by the data, and neglected final state hadron mass effects can be significant. Gluon fragmentation shows a rather different pattern of medium modification, with a much more noticeable drop at large z , combined with a sizable enhancement at intermediate z . Notice that the low z behavior of the gluon nFFs is crucial for reproducing the x_{Bj} dependence shown by the SIDIS rates and therefore it is relatively well constrained by these data. On the contrary, the large z behavior is related to the suppression of the RHIC cross sections at low p_T that need better understanding from the theoretical side.

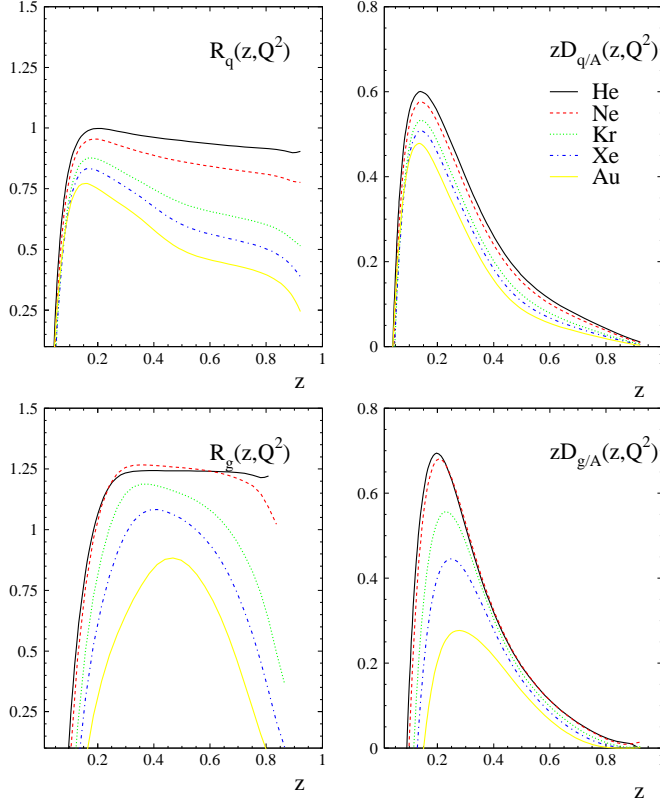


Figure 4: nFFs and rates at $Q^2 = 10 \text{ GeV}^2$

3 Conclusions

We have explored the feasibility of reproducing the main features of data sensitive to medium induced modifications of fragmentation functions in a factorized QCD framework at NLO accuracy based on a convolutional approach. The nice agreement found encourages us to further pursue this approach and extend it to hadrons species other than pions.

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